**Supplementary material**

**Population dynamics of free-roaming dogs and implications for population control**

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### 1. Details of study regions, study sites and historical dog population management

Pescara is located in southern Italy in the Abruzzo region and has an oceanic climate (Peel, Finlayson, & Mcmahon, 2007). The province has a total area of 1,230km$^2$ and a population size of 318,909 ("Istituto Nazionale Di Statistica," n.d.). Population density is 123 people per km$^2$ (State Statistics Service of Ukraine, n.d.). Lviv is located in the west of Ukraine and has a temperate continental climate (Peel et al., 2007). The region covers 21,833km$^2$ and the population size is 2,522,021 (State Statistics Service of Ukraine, 2018). The population density is 115 people per km$^2$ across the region. Study regions were selected where networks were established to facilitate data collection, including sites where there was existing historical information on dog population management. In Pescara, this network was the Veterinary Services – Pescara Province Local Health Unit, an organisation involved in dog population management. In Lviv, these networks were VIER PFOTEN International, the Lviv local

Communal Enterprise, and Animal-id.info. Both VIER PFOTEN International and the Lviv local Communal Enterprise have been involved in dog population management in Lviv.

Prior to the fieldwork commencing, pilot trips to the study sites were conducted to check the suitability of the selected study sites for: (i) accessibility (i.e., no private land such as industrial areas where access is prohibited); and (ii) the presence of free-roaming dogs. Data collected during the pilot trip was not included in the analysis. The study sites remain anonymous as a condition of data sharing with the local networks.

*Table 1. Numbers of dogs caught, neutered and released to study sites in Pescara, Italy and Lviv, Ukraine between 2014 and 2019. Sources: Veterinary Services – Pescara Province Local Health Unit for Pescara; and local Communal Enterprise for Lviv.*

| | Study site | Number of dogs released to study site | | | | | | |
| | | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 (Jan-Jul) | Total |
|---|---|---|---|---|---|---|---|---|
| Pescara | One | 5 | 11 | 7 | 13 | 4 | 4 | 44 |
| | Two | 4 | 8 | 6 | 10 | 6 | 3 | 37 |
| | Three | 3 | 8 | 6 | 3 | 4 | 10 | 34 |
| | Four | 14 | 10 | 22 | 4 | 9 | 5 | 64 |
| Lviv | One | 0 | 0 | 69 | 105 | 89 | 7 | 270 |
| | Two | 0 | 0 | 34 | 58 | 51 | 20 | 163 |
| | Three | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Four | 0 | 0 | 1 | 0 | 0 | 0 | 1 |

## 2. Survey details, timings and weather

Survey routes were designed to maximise street coverage across the study site and avoid enclosed areas as a safety measure to reduce the risk of dog attack. Roads without a pavement were excluded as a traffic safety measure. The street surveys followed the same route across both the secondary and primary sampling days. Although this did not occur during this study, surveys were to be terminated for any days that may show abnormal free-roaming dog numbers, for example due to unusual weather (e.g. extremely high or low temperature or prolonged heavy rain).

All surveys took place between 06:00 and 10:00. In Ukraine, out of 60 surveys, 58 (97%) surveys took place between 06:30 and 09:30, one survey (2%) was missed due to illness, and one survey (2%) began at 06:00 due to logistical constraints. In Italy, out of the 60 surveys, 59 (98%) took place between 06:30 and 09:30, and one survey began at 06:00 due to logistical constraints. For the survey that was missed due to illness, NA's were included in the array of capture histories ($\gamma^{(i \times t \times s)}$) for study site one in Lviv for primary period three, secondary sampling period two. For the predictor variables, temperature and rainfall (no rainfall) was recorded using records in weather.com, the missed survey day was a weekday and market event was recorded as NA.

*Table 2. Survey timings, distance and length (minimum, maximum and mean) in study sites in Pescara, Italy and Lviv, Ukraine.*

| Study region | Study site | Distance (km) | Survey time (minutes) | | | Start time | | | End time | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Pescara | One | 3.38 | 49 | 97 | 63 | 06:53 | 07:08 | 06:59 | 07:44 | 08:30 | 08:01 |
| | Two | 6.20 | 49 | 81 | 67 | 06:55 | 07:09 | 07:00 | 07:49 | 08:17 | 08:07 |
| | Three | 8.79 | 76 | 128 | 92 | 06:52 | 07:15 | 07:01 | 08:16 | 09:00 | 08:33 |
| | Four | 6.50 | 77 | 106 | 87 | 06:00* | 07:21 | 06:57 | 07:18 | 08:45 | 08:24 |
| Lviv | One | 8.44 | 77 | 153 | 99 | 06:50 | 07:13** | 07:00 | 08:14 | 08:57 | 08:32 |
| | Two | 7.20 | 86 | 112 | 95 | 06:45 | 07:30** | 07:01 | 08:13 | 09:01 | 08:36 |
| | Three | 9.43 | 74 | 121 | 101 | 05:58* | 07:40** | 07:01 | 07:53 | 09:14 | 08:48 |
| | Four | 7.64 | 86 | 135 | 107 | 06:50 | 07:31** | 07:05 | 08:26 | 09:27 | 08:51 |

* Survey began earlier due to logistical constraints.

** Survey began later due to daylight hours (sunrise at later time).

*Table 3. Primary and secondary sampling period timings, temperature and weather conditions in Pescara, Italy.*

| Primary sampling period | Study site | Secondary sampling period | Date | Start Temp | Finish Temp | Mean temperature (°C) | Rain | Market event | Start time | Finish time | Survey length (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| One (April 2018) | | 1 | 11/04/2018 | 11 | 11 | 11 | Yes | No | 07:00 | 07:57 | 57 |
| | One | 2 | 12/04/2018 | 13 | 13 | 13 | No | No | 07:00 | 08:01 | 61 |
| | | 3 | 13/04/2018 | 11 | 12 | 11.5 | No | No | 06:53 | 08:30 | 97 |
| | | 1 | 14/04/2018 | 11 | 12 | 11.5 | No | No | 06:55 | 08:16 | 81 |
| | Two | 2 | 15/04/2018 | 13 | 13 | 13 | No | No | 06:55 | 08:16 | 81 |
| | | 3 | 16/04/2018 | 14 | 14 | 14 | No | No | 07:00 | 08:09 | 69 |
| | | 1 | 17/04/2018 | 12 | 13 | 12.5 | No | No | 06:52 | 08:26 | 94 |
| | Three | 2 | 18/04/2018 | 14 | 14 | 14 | No | No | 06:58 | 08:42 | 105 |
| | | 3 | 19/04/2018 | 13 | 16 | 14.5 | No | No | 06:52 | 09:00 | 128 |
| | | 1 | 20/04/2018 | 14 | 17 | 15.5 | No | No | 06:55 | 08:41 | 106 |
| | Four | 2 | 21/04/2018 | 14 | 14 | 14 | No | No | 06:49 | 08:23 | 94 |
| | | 3 | 22/04/2018 | 12 | 14 | 13 | No | No | 06:50 | 08:16 | 86 |
| Two (July 2018) | | 1 | 06/07/2018 | 22 | 23 | 22.5 | No | No | 06:55 | 08:03 | 68 |
| | One | 2 | 07/07/2018 | 20 | 22 | 21 | No | No | 07:00 | 08:20 | 80 |
| | | 3 | 08/07/2018 | 20 | 22 | 21 | No | No | 06:55 | 08:10 | 75 |
| | | 1 | 09/07/2018 | 21 | 24 | 22.5 | No | No | 07:03 | 08:10 | 67 |
| | Two | 2 | 10/07/2018 | 19 | 22 | 20.5 | No | No | 06:55 | 08:12 | 77 |
| | | 3 | 11/07/2018 | 24 | 24 | 24 | No | No | 07:00 | 08:00 | 60 |
| | Three | 1 | 12/07/2018 | 20 | 23 | 21.5 | No | No | 07:09 | 08:57 | 108 |

| Primary sampling period | Study site | Secondary sampling period | Date | Start Temp | Finish Temp | Mean temperature (ºC) | Rain | Market event | Start time | Finish time | Survey length (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 13/07/2018 | 22 | 24 | 23 | No | No | 07:00 | 08:34 | 94 |
| | | 3 | 14/07/2018 | 21 | 24 | 22.5 | No | Yes | 07:06 | 08:36 | 90 |
| | | 1 | 15/07/2018 | 23 | 26 | 24.5 | No | No | 07:05 | 08:39 | 94 |
| | Four | 2 | 16/07/2018 | 23 | 26 | 24.5 | No | No | 07:05 | 08:33 | 88 |
| | | 3 | 17/07/2018 | 19 | 19 | 19 | Yes | No | 07:01 | 08:20 | 79 |
| | | 1 | 02/10/2018 | 12 | 13 | 12.5 | No | No | 07:00 | 08:00 | 60 |
| | One | 2 | 03/10/2018 | 12 | 13 | 12.5 | No | No | 07:00 | 08:00 | 60 |
| | | 3 | 04/10/2018 | 13 | 14 | 13.5 | No | No | 06:55 | 08:02 | 67 |
| | | 1 | 05/10/2018 | 16 | 15 | 15.5 | Yes | Yes | 07:06 | 08:09 | 63 |
| | Two | 2 | 06/10/2018 | 14 | 16 | 15 | Yes | No | 07:01 | 08:17 | 76 |
| Three (October 2018) | | 3 | 07/10/2018 | 14 | 16 | 15 | No | No | 06:58 | 08:10 | 72 |
| | | 1 | 08/10/2018 | 13 | 14.5 | 13.75 | No | No | 07:00 | 08:32 | 92 |
| | Three | 2 | 09/10/2018 | 14 | 15 | 14.5 | No | No | 07:02 | 08:34 | 92 |
| | | 3 | 10/10/2018 | 14 | 15 | 14.5 | No | No | 07:15 | 08:45 | 90 |
| | | 1 | 11/10/2018 | 14 | 16 | 15 | No | No | 07:15 | 08:45 | 90 |
| | Four | 2 | 12/10/2018 | 17 | 17 | 17 | No | No | 06:56 | 08:22 | 86 |
| | | 3 | 13/10/2018 | 13 | 14 | 13.5 | No | No | 07:21 | 08:43 | 82 |
| | | 1 | 07/04/2019 | 8 | 9 | 8.5 | Yes | No | 07:00 | 07:51 | 51 |
| Four (April 2019) | One | 2 | 08/04/2019 | 10 | 9 | 9.5 | No | No | 07:08 | 08:04 | 56 |
| | | 3 | 09/04/2019 | 12 | 12 | 12 | No | No | 06:55 | 07:44 | 49 |
| | Two | 1 | 10/04/2019 | 9 | 10 | 9.5 | No | No | 07:00 | 08:03 | 63 |

| Primary sampling period | Study site | Secondary sampling period | Date | Start Temp | Finish Temp | Mean temperature (°C) | Rain | Market event | Start time | Finish time | Survey length (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 11/04/2019 | 7 | 9 | 8 | No | No | 07:09 | 08:07 | 58 |
| | | 3 | 12/04/2019 | 7 | 9 | 8 | No | No | 07:00 | 07:49 | 49 |
| | | 1 | 13/04/2019 | 7 | 7 | 7 | No | Yes | 07:00 | 08:23 | 83 |
| | Three | 2 | 14/04/2019 | 7 | 8 | 7.5 | No | No | 07:00 | 08:23 | 83 |
| | | 3 | 15/04/2019 | 7 | 7 | 7 | Yes | No | 07:00 | 08:22 | 82 |
| | | 1 | 16/04/2019 | 9 | 10 | 9.5 | No | No | 07:00 | 08:20 | 80 |
| | Four | 2 | 17/04/2019 | 9 | 12 | 10.5 | No | Yes | 07:00 | 08:23 | 83 |
| | | 3 | 18/04/2019 | 11 | 12 | 11.5 | No | No | 07:00 | 08:44 | 104 |
| | | 1 | 09/07/2019 | 25 | 26 | 25.5 | No | No | 07:05 | 08:04 | 59 |
| | One | 2 | 10/07/2019 | 23 | 23 | 23 | No | No | 07:00 | 07:52 | 52 |
| | | 3 | 11/07/2019 | 19 | 21 | 20 | No | Yes | 07:00 | 07:50 | 50 |
| | | 1 | 12/07/2019 | 19 | 22 | 20.5 | No | Yes | 06:57 | 08:06 | 69 |
| | Two | 2 | 13/07/2019 | 20 | 22 | 21 | No | No | 07:03 | 08:00 | 57 |
| | | 3 | 14/07/2019 | 18 | 19 | 18.5 | No | No | 07:05 | 08:02 | 57 |
| Five (July 2019) | | 1 | 15/07/2019 | 17 | 19 | 18 | No | No | 07:14 | 08:33 | 79 |
| | Three | 2 | 16/07/2019 | 17 | 18 | 17.5 | No | No | 07:00 | 08:16 | 76 |
| | | 3 | 17/07/2019 | 17 | 19 | 18 | No | No | 07:01 | 08:26 | 85 |
| | | 1 | 18/07/2019 | 18 | 22 | 20 | No | No | 07:00 | 08:20 | 80 |
| | Four | 2 | 19/07/2019 | 19 | 21 | 20 | No | No | 07:00 | 08:17 | 77 |
| | | 3 | 20/07/2019 | 19 | 22 | 20.5 | No | No | 06:00 | 07:18 | 78 |

*Table 4. Primary and secondary sampling period timings, temperature and weather conditions in Lviv, Ukraine.*

| Primary sampling period | Study site | Secondary sampling period | Date | Start Temp | Finish Temp | Mean Temperature (°C) | Rain | Market event | Start time | Finish time | Survey length (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| One (April 2018) | One | 1 | 01/05/2018 | 12 | 19 | 15.5 | No | No | 07:00 | 08:57 | 117 |
| | | 2 | 02/05/2018 | 11 | 17 | 14 | No | No | 06:55 | 08:53 | 118 |
| | | 3 | 03/05/2018 | 14 | 17 | 15.5 | No | No | 06:50 | 08:29 | 99 |
| | Two | 1 | 04/05/2018 | 10 | 17 | 13.5 | No | No | 06:50 | 08:42 | 112 |
| | | 2 | 05/05/2018 | 13 | 14 | 13.5 | No | No | 06:45 | 08:21 | 96 |
| | | 3 | 06/05/2018 | 11 | 11 | 11 | No | No | 06:45 | 08:13 | 88 |
| | Three | 1 | 07/05/2018 | 6 | 24 | 15 | No | No | 06:55 | 08:55 | 120 |
| | | 2 | 08/05/2018 | 11 | 13 | 12 | No | No | 06:55 | 08:50 | 115 |
| | | 3 | 09/05/2018 | 14 | 17 | 15.5 | No | No | 06:50 | 08:45 | 85 |
| | Four | 1 | 10/05/2018 | 12 | 17 | 14.5 | No | No | 06:55 | 08:50 | 115 |
| | | 2 | 11/05/2018 | 10 | 16 | 13 | No | No | 06:55 | 08:26 | 91 |
| | | 3 | 12/05/2018 | 9 | 13 | 11 | No | No | 06:50 | 08:34 | 104 |
| Two (July 2018) | One | 1 | 20/07/2018 | 18 | 19 | 18.5 | No | No | 07:00 | 08:28 | 88 |
| | | 2 | 21/07/2018 | 17 | 19 | 18 | No | Yes | 07:00 | 08:47 | 107 |
| | | 3 | 22/07/2018 | 14 | 18 | 16 | No | No | 07:00 | 08:24 | 84 |
| | Two | 1 | 23/07/2018 | 18 | 19 | 18.5 | No | No | 07:00 | 08:41 | 101 |
| | | 2 | 24/07/2018 | 18 | 19 | 18.5 | Yes | No | 07:00 | 08:36 | 96 |
| | | 3 | 25/07/2018 | 18 | 18 | 18 | No | No | 07:00 | 08:42 | 102 |
| | Three | 1 | 30/07/2018 | 17 | 21 | 19 | No | No | 07:00 | 09:14 | 74 |
| | | 2 | 31/07/2018 | 18 | 19 | 18.5 | Yes | No | 07:00 | 08:48 | 108 |

| Primary sampling period | Study site | Secondary sampling period | Date | Start Temp | Finish Temp | Mean Temperature (°C) | Rain | Market event | Start time | Finish time | Survey length (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 | 01/08/2018 | 18 | 19 | 18.5 | No | No | 05:58 | 07:53 | 115 |
| | | 1 | 27/07/2018 | 17 | 21 | 19 | No | No | 06:50 | 09:05 | 135 |
| | Four | 2 | 28/07/2018 | 17 | 21 | 19 | No | No | 06:55 | 08:58 | 124 |
| | | 3 | 29/07/2018 | 20 | 21 | 20.5 | No | No | 07:00 | 09:07 | 127 |
| | | 1 | 16/10/2018 | 6 | 7 | 6.5 | No | No | 06:55 | 08:28 | 94 |
| | One | 2 | 17/10/2018* | 5 | 7 | 6 | NA | NA | NA | NA | NA |
| | | 3 | 18/10/2018 | 7 | 7 | 7 | No | No | 07:13 | 08:46 | 153 |
| | | 1 | 19/10/2018 | 7 | 9 | 8 | No | No | 07:20 | 08:50 | 90 |
| | Two | 2 | 20/10/2018 | 8 | 9 | 8.5 | No | No | 07:30 | 09:01 | 91 |
| Three (October 2018) | | 3 | 21/10/2018 | 7 | 7 | 7 | Yes | No | 07:28 | 09:00 | 92 |
| | | 1 | 22/10/2018 | 0 | 1 | 0.5 | No | No | 07:27 | 09:07 | 100 |
| | Three | 2 | 23/10/2018 | 6 | 6 | 6 | Yes | No | 07:30 | 09:07 | 97 |
| | | 3 | 24/10/2018 | 6 | 6 | 6 | Yes | No | 07:40 | 09:11 | 91 |
| | | 1 | 25/10/2018 | 3 | 3 | 3 | No | No | 07:31 | 09:27 | 122 |
| | Four | 2 | 26/10/2018 | 6 | 6 | 6 | No | No | 07:30 | 09:08 | 98 |
| | | 3 | 27/10/2018 | 8 | 8 | 8 | No | Yes | 07:30 | 09:13 | 103 |
| | | 1 | 26/04/2019 | 9 | 15 | 12 | No | Yes | 07:00 | 08:36 | 94 |
| | One | 2 | 27/04/2019 | 16 | 17 | 16.5 | No | No | 07:00 | 08:25 | 85 |
| Four (April 2019) | | 3 | 28/04/2019 | 12 | 12 | 12 | No | No | 06:57 | 08:14 | 77 |
| | | 1 | 29/04/2019 | 9 | 10 | 9.5 | Yes | No | 07:00 | 08:26 | 86 |
| | Two | 2 | 30/04/2019 | 9 | 10 | 9.5 | Yes | No | 06:50 | 08:21 | 91 |
| | | 3 | 01/05/2019 | 8 | 8 | 8 | Yes | No | 06:55 | 08:24 | 89 |

| Primary sampling period | Study site | Secondary sampling period | Date | Start Temp | Finish Temp | Mean Temperature (°C) | Rain | Market event | Start time | Finish time | Survey length (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 02/05/2019 | 7 | 10 | 8.5 | No | No | 06:57 | 08:58 | 121 |
| | Three | 2 | 03/05/2019 | 9 | 12 | 10.5 | No | No | 07:08 | 08:50 | 102 |
| | | 3 | 04/05/2019 | 8 | 8 | 8 | No | No | 07:02 | 08:49 | 107 |
| | | 1 | 05/05/2019 | 9 | 9 | 9 | Yes | No | 07:06 | 08:49 | 103 |
| | Four | 2 | 06/05/2019 | 5 | 5 | 5 | Yes | No | 07:02 | 08:51 | 109 |
| | | 3 | 07/05/2019 | 5 | 6 | 5.5 | No | No | 07:04 | 08:51 | 107 |
| | | 1 | 21/07/2019 | 15 | 19 | 17 | No | No | 07:02 | 08:20 | 78 |
| | One | 2 | 22/07/2019 | 16 | 17 | 16.5 | No | No | 07:05 | 08:28 | 83 |
| | | 3 | 23/07/2019 | 16 | 18 | 17 | No | No | 07:00 | 08:18 | 78 |
| | | 1 | 24/07/2019 | 16 | 17 | 16.5 | No | No | 07:00 | 08:32 | 92 |
| | Two | 2 | 25/07/2019 | 16 | 17 | 16.5 | No | No | 07:00 | 08:36 | 96 |
| Five (July 2019) | | 3 | 26/07/2019 | 16 | 18 | 17 | No | No | 07:02 | 08:44 | 102 |
| | | 1 | 27/07/2019 | 14 | 17 | 15.5 | No | No | 07:01 | 08:38 | 97 |
| | Three | 2 | 28/07/2019 | 20 | 21 | 20.5 | No | No | 07:00 | 08:27 | 87 |
| | | 3 | 29/07/2019 | 19 | 23 | 21 | No | No | 07:00 | 08:35 | 95 |
| | | 1 | 30/07/2019 | 18 | 19 | 18.5 | No | No | 07:03 | 08:32 | 89 |
| | Four | 2 | 31/07/2019 | 18 | 19 | 18.5 | No | No | 07:00 | 08:26 | 86 |
| | | 3 | 01/08/2019 | 16 | 18 | 17 | No | No | 07:07 | 08:33 | 86 |

\* Primary sampling period three, secondary sampling period two was missed due to fieldworker illness

Figure *1. Examples of distinctiveness ratings of dogs identified across primary sampling periods: A1-3 of distinctiveness 1 (distinct with unique markings); B1-3 of distinctiveness 2 (moderately distinct, with some identifiable colouring/markings); and C1-3 of distinctiveness 3 (indistinct, mono-coloured, minimal markings).*

### 3. Details of hierarchical Bayesian hidden Markov model of Pollock's robust design

It is challenging to estimate demographic parameters using mark-recapture data because several ecological processes can lead to the mark-recapture histories that are observed. For example, individuals may be present in the population, but not detected during surveys, meaning their presence or absence is not an accurate estimate of whether an individual is contributing to the population processes. To deal with these challenges, a hierarchical Bayesian hidden Markov model of Pollock's closed robust design was used to analyse the mark-recapture histories for both Pescara and Lviv. Hidden Markov models deal with these challenges as they allow the underlying latent states of dogs (e.g. their presence or absence in the population) to be estimated depending on observations during the mark-recapture surveys (i.e. their capture histories).

Parameter-expansion and data augmentation:

Parameter-expansion and data augmentation simply involved adding a list of all-zero capture histories to the data to account for individuals that were never observed over the duration of the mark-recapture study. This allowed the states of both the individuals that were observed and those that were unobserved throughout the study (i.e. those that had very low detection probabilities) to be modelled, allowing better inferences to be made about the true population (Kery & Schaub, 2011; Rankin et al., 2016; Royle & Dorazio, 2008).

Specifically, parameter expanded data-augmentation deals with the computational challenges of variable dimension space when modelling full-capture histories and random effects for individual dogs (Kery & Schaub, 2011; Rankin et al., 2016; Royle & Dorazio, 2012; Tanner & Wong, 1987). In this study, a set of *pseudo-individuals* with all-zero (*unobserved*) capture histories were included in the list of capture histories for each of the study sites. The augmented dataset ($m$) totalled 150 individuals at each primary period in Pescara and 300 individuals at each primary period in Lviv. The augmented dataset ($m$) included the observed number of individuals ($n$) plus a number of *pseudo-individuals*, and the estimated number of individuals ($N$) lies between $n$ and $m$. The *pseudo-individuals* did not affect the estimates of detection probability ($\delta$), apparent survival ($\varphi$) or population size ($N$) but allowed more accurate estimation of the parameters using simpler computation. To test that the dataset included enough *pseudo-individuals*, the posterior

distributions of *N* were plotted to ensure the distribution was not truncated to the right (Figures 2-6. The uncaptured *pseudo-individuals* made up the population of individuals that were available for recruitment into the study population and allowed modelling of individual random effects for dogs that were missed throughout all secondary sampling periods.

### *3.1.   Entry probability*

This provided the fraction of the true population ('super-population'; total number of dogs that had ever been in the study site across all primary periods) of individuals entering the study site at time *t*, given they had not entered at a previous time point. The entry probability must sum to one across all primary sampling periods and individuals were assumed to be in the *not yet entered* state prior to the first primary period. This means the entry probability calculated for the first primary period was less interpretable; instead, entry probabilities after the first primary period were reported. We also estimated a per capita entry probability (*f*), as described by Kery and Schaub (2011). Per capita entry probability describes the fraction of new recruits at primary period *t* per individual dog alive and in the study site at primary period *t*. This was calculated by Equation 1. Population growth ($l_t$) was calculated by dividing the estimated population size at period *t* ($N_t$) by the estimated population size at primary period $N_{t-1}$ (Equation 2). **Error! Reference source not found.** outlines the parameters calculated for each study site.

Equation 1. Per capita entry probability.

$$f_t = \frac{E_t \times W}{N_t}$$

Equation 2. Population growth

$$\lambda_t = \frac{N_t}{N_{t-1}}$$

*Table 5. Description of parameters calculated for each study site in study regions.*

| Parameter | Description |
|---|---|
| $Z^{(m \times t)}$ | Matrix of the possible latent states (*not-yet-entered; alive; dead*) for each individual (including *pseudo-individuals*) at each *t* primary sampling period. |

| Parameter | Description |
|---|---|
| $n$ | Total number of dogs individually identified throughout the duration of the study. |
| $N_t$ | Total number of dogs alive and available for observation during primary sampling period $t$. |
| $m$ | Total number of dogs, including observed and unobserved *pseudo-individuals*. |
| $\gamma^{(m \times t \times s)}$ | Array of capture histories for all individually identified dogs and the parameter expanded data augmented *pseudo-individuals*. |
| $\gamma^{(i \times t \times s)}$ | Array of capture histories for all individuals *observed* in $s$ secondary sampling periods throughout $t$ primary sampling periods. |
| $W$ | Superpopulation: Total number of dogs that have ever been in the study site across all primary sampling periods. |
| $\varphi_{ti}$ | Apparent survival of individual dog between $t$ and $t^{+1}$ primary sampling period. |
| $\delta_{ti}$ | Probability of observing a dog, given it is alive, in secondary sampling period $s$ within primary sampling period $t$. |
| $\psi_{ti}$ | Probability of recruitment – an individual dog transitioning from *not yet entered* at $t^{-1}$ to *alive* at $t$ primary sampling period. As described, this is a nuisance parameter that is required to describe the model. |
| $E_{ti}$ | Proportion of superpopulation entering at each primary period $t$, given they have not already entered. |
| $f_t$ | Per capita entry probability: the fraction of new recruits at primary period $t$ per individual dog alive and in the study site at primary period $t$. |
| $\lambda$ | Population growth (Equation 2). |
| $M_t$ | Matrix of time intervals between each primary sampling period. |
| $M_d$ | Matrix of distances between study sites. |

## 3.2. Model running

Data from study sites in Pescara and Lviv were run in the same model, but parameter estimates were not informed by capture histories between countries (i.e. parameter estimates for study sites in Pescara were not informed by those estimated for study sites in Lviv).
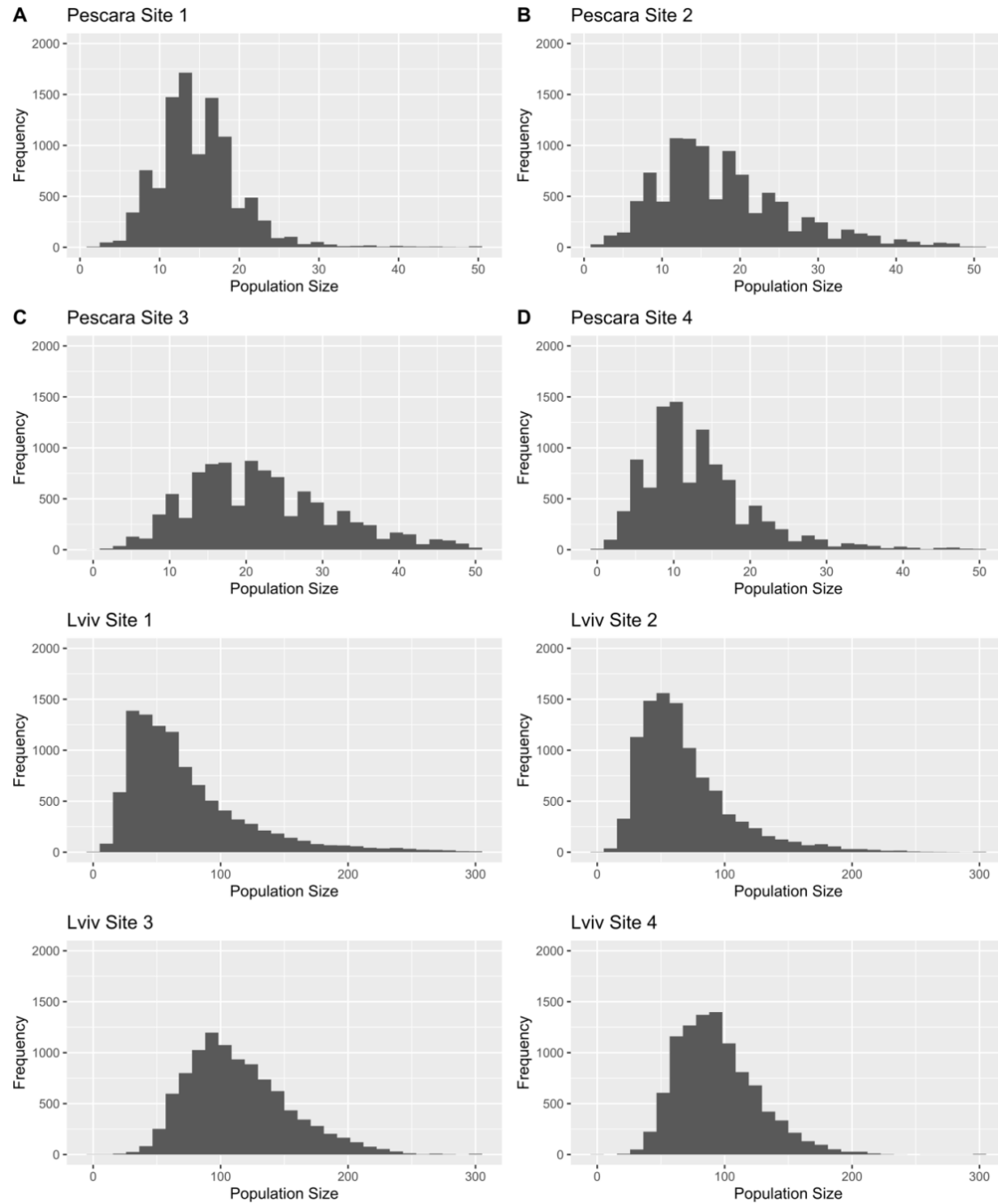
*Figure 2. Posterior distribution of estimated population size (N) at primary sampling period 1 in study sites in Pescara and Lviv.*
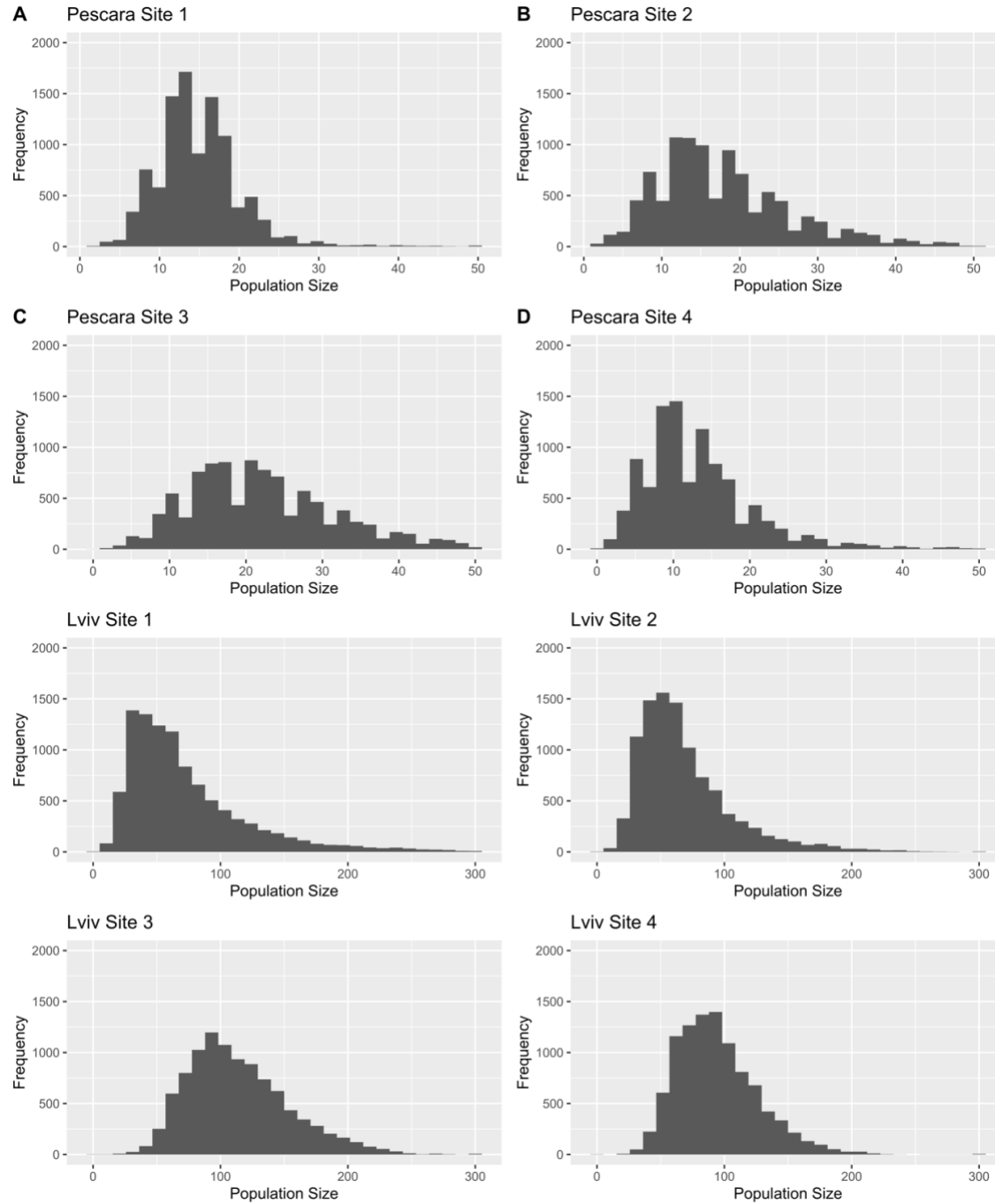
*Figure 3. Posterior distribution of estimated population size (N) at primary sampling period 2 in study sites in Pescara and Lviv.*
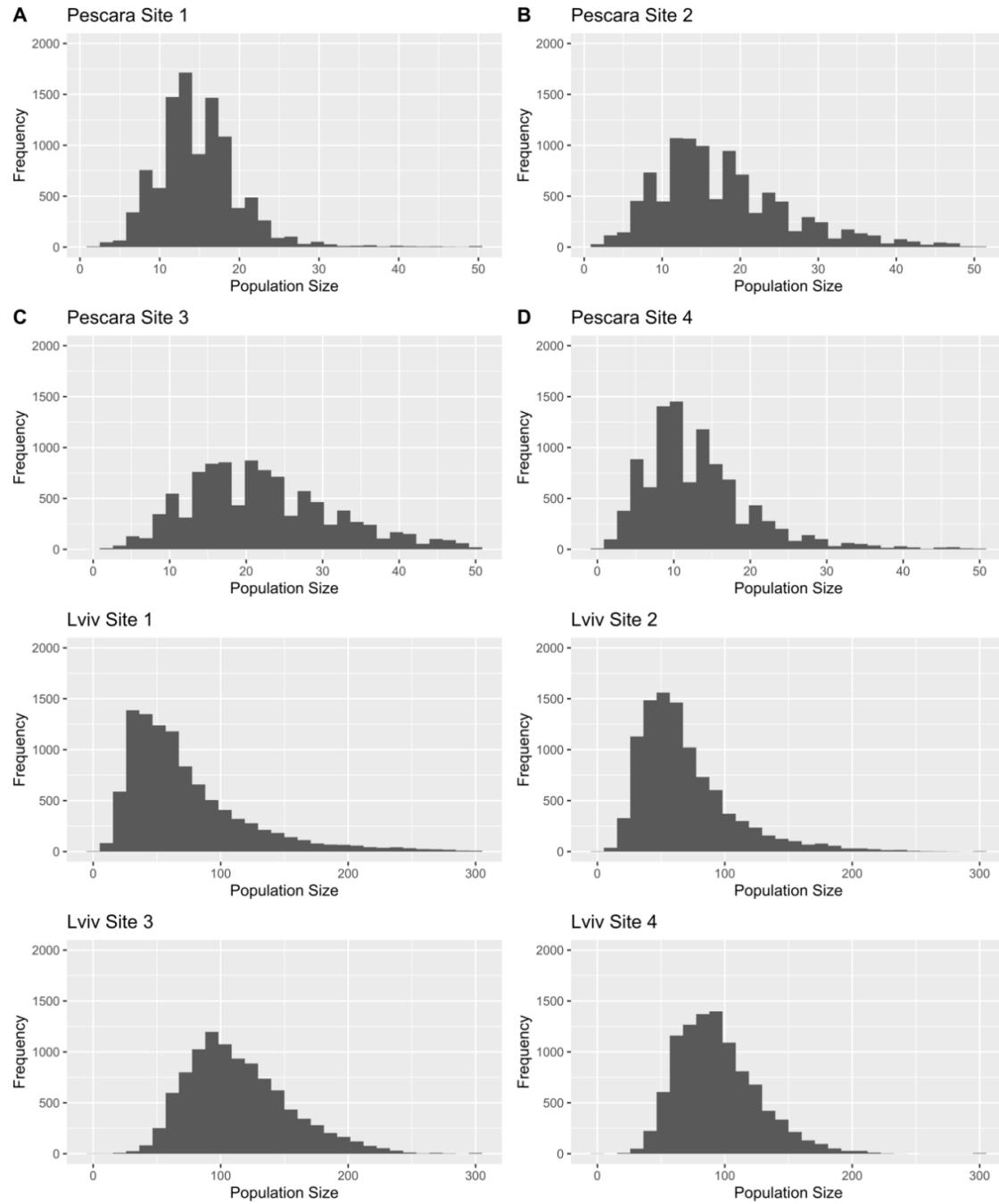
*Figure 4. Posterior distribution of estimated population size (N) at primary sampling period 3 in study sites in Pescara and Lviv.*
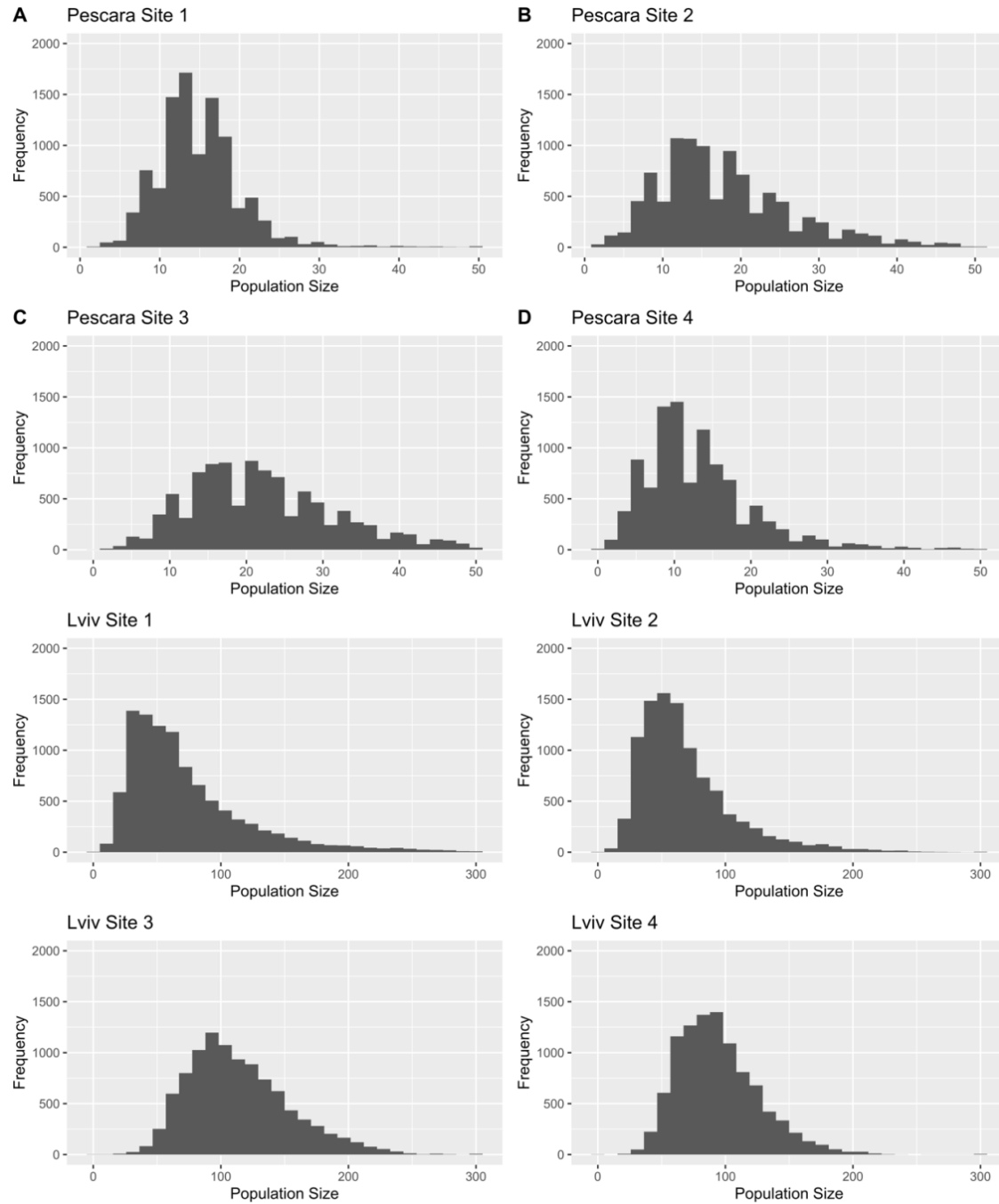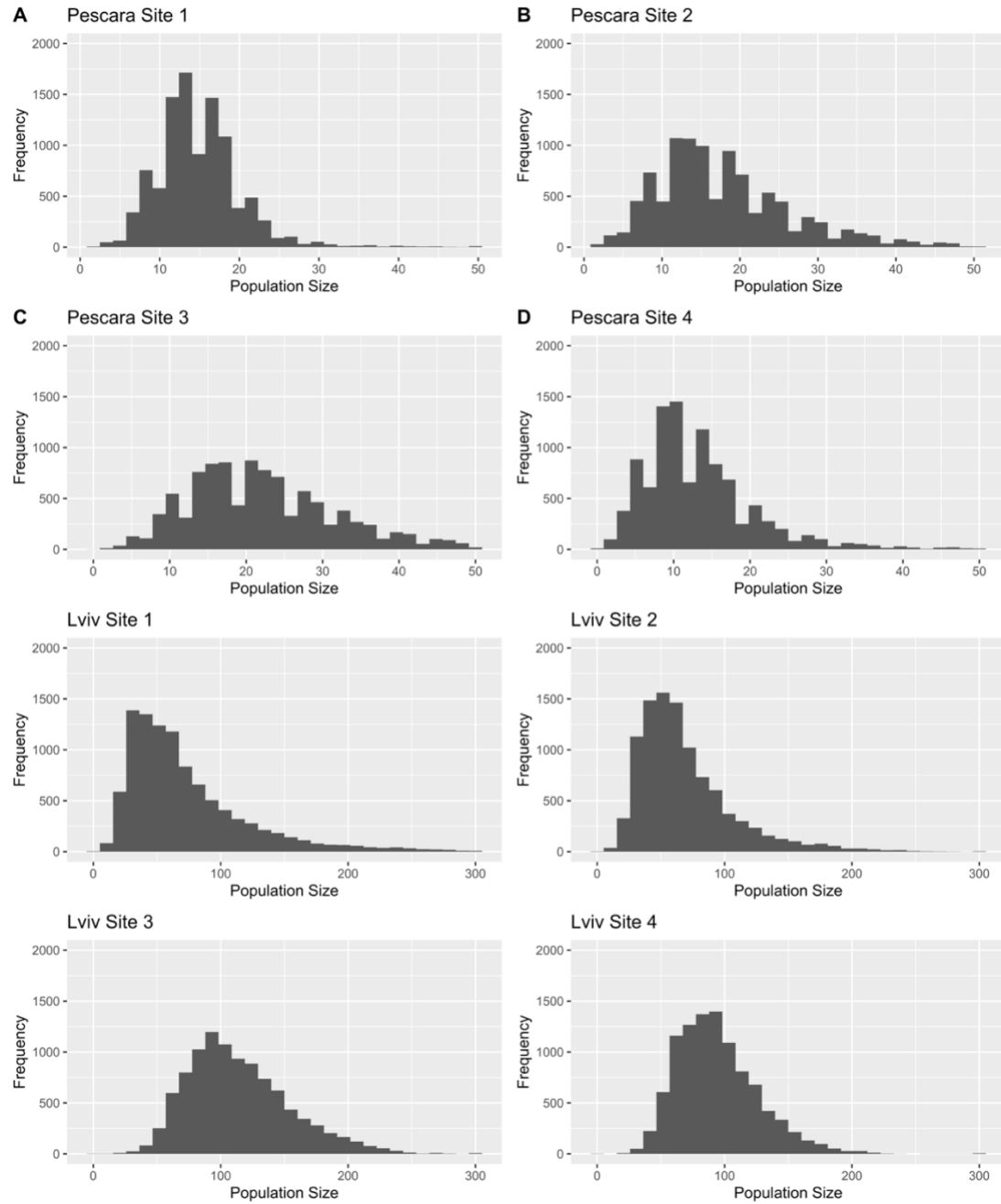
*Figure 5. Posterior distribution of estimated population size (N) at primary sampling period 4 in study sites in Pescara and Lviv.*

*Figure 6. Posterior distribution of estimated population size (N) at primary sampling period 5 in study sites in Pescara and Lviv.*

## 4. Results

In total, five primary sampling periods were completed in both Pescara and Lviv. Fifteen secondary sampling periods were completed in study sites in Pescara, and 14 secondary sampling periods were completed in Lviv between April 2018 and July 2019. No surveys were terminated due to conditions that may have shown abnormal free-roaming dog numbers. One survey (one secondary sampling period) did not occur due to fieldworker illness in study site one in Lviv during primary sampling period three (details of how this missing data was dealt with in the model are in supplementary information).

*Table 6. Probability of apparent survival and detection for primary sampling periods (averaged across individuals and study sites) and study sites (averaged across individuals and primary periods) in Pescara, Italy.*

| | | Mean | 2.5% CI | 97.5% CI |
|---|---|---|---|---|
| Average probability of apparent survival | Primary Period 1 to 2 (3-month interval) | 0.82 | 0.58 | 1.00 |
| | Primary Period 2 to 3 (3-month interval) | 0.74 | 0.44 | 0.99 |
| | Primary Period 3 to 4 (6-month interval) | 0.74 | 0.43 | 1.00 |
| | Primary Period 4 to 5 (3-month interval) | 0.79 | 0.47 | 1.00 |
| | study site 1 | 0.77 | 0.48 | 0.98 |
| | study site 2 | 0.71 | 0.36 | 0.99 |
| | study site 3 | 0.71 | 0.33 | 1.00 |
| | study site 4 | 0.77 | 0.45 | 1.00 |
| Average probability of detecting a dog | Primary Period 1 | 0.23 | 0.04 | 0.47 |
| | Primary Period 2 | 0.18 | 0.02 | 0.40 |
| | Primary Period 3 | 0.20 | 0.03 | 0.42 |
| | Primary Period 4 | 0.18 | 0.02 | 0.40 |
| | Primary Period 5 | 0.25 | 0.04 | 0.52 |
| | study site 1 | 0.41 | 0.14 | 0.74 |
| | study site 2 | 0.18 | 0.01 | 0.46 |
| | study site 3 | 0.11 | 0.01 | 0.27 |
| | study site 4 | 0.22 | 0.01 | 0.51 |

*Table 7. Probability of apparent survival and detection for primary sampling periods (averaged across individuals and study sites) and study sites (averaged across individuals and primary periods) in Lviv, Ukraine.*

| | | Mean | 2.5% CI | 97.5% CI |
|---|---|---|---|---|
| Average probability of apparent survival | Primary Period 1 to 2 (3-month interval) | 0.83 | 0.61 | 1.00 |
| | Primary Period 2 to 3(3-month interval) | 0.76 | 0.50 | 0.97 |
| | Primary Period 3 to 4 (6-month interval) | 0.90 | 0.73 | 1.00 |
| | Primary Period 4 to 5(3-month interval) | 0.73 | 0.44 | 0.97 |
| | study site 1 | 0.83 | 0.56 | 1.00 |
| | study site 2 | 0.82 | 0.57 | 1.00 |
| | study site 3 | 0.75 | 0.46 | 0.98 |
| | study site 4 | 0.67 | 0.35 | 0.93 |
| Average probability of detecting a dog | Primary Period 1 | 0.08 | 0.00 | 0.21 |
| | Primary Period 2 | 0.12 | 0.01 | 0.30 |
| | Primary Period 3 | 0.14 | 0.01 | 0.34 |
| | Primary Period 4 | 0.10 | 0.01 | 0.26 |
| | Primary Period 5 | 0.10 | 0.01 | 0.25 |
| | study site 1 | 0.07 | 0.00 | 0.22 |
| | study site 2 | 0.11 | 0.00 | 0.31 |
| | study site 3 | 0.10 | 0.00 | 0.28 |
| | study site 4 | 0.16 | 0.01 | 0.41 |

*Table 8. Standard deviations for between-dog effects on survival and detection on log odds scale.*

| | Study site | Pescara | | | Lviv | | |
|---|---|---|---|---|---|---|---|
| | | **Mean** | **2.5% CI** | **97.5% CI** | **Mean** | **2.5% CI** | **97.5% CI** |
| Survival ($\varphi$) | 1 | 0.95 | 0.00 | 2.14 | 1.02 | 0.00 | 2.31 |
| | 2 | 1.01 | 0.00 | 2.30 | 0.77 | 0.00 | 1.87 |
| | 3 | 0.85 | 0.00 | 2.06 | 1.22 | 0.00 | 2.47 |
| | 4 | 0.78 | 0.00 | 1.92 | 0.63 | 0.00 | 1.54 |
| Detection ($\delta$) | 1 | 0.55 | 0.00 | 1.37 | 1.58 | 0.81 | 2.34 |
| | 2 | 1.47 | 0.45 | 2.44 | 1.54 | 0.81 | 2.31 |
| | 3 | 0.48 | 0.00 | 1.17 | 1.85 | 1.20 | 2.49 |
| | 4 | 1.05 | 0.04 | 2.00 | 1.67 | 1.01 | 2.31 |

*Table 9. Comparison of mean apparent survival and detection as odds ratios between different study sites in Pescara, Italy and Lviv, Ukraine.*

| Average probability | Study sites | Pescara | | | Lviv | | |
|---|---|---|---|---|---|---|---|
| | | Mean | 2.5% CI | 97.5% CI | Mean | 2.5% CI | 97.5% CI |
| Apparent survival ($\varphi$) | 1 and 2 | 2.19 | 0.01 | 6.50 | 2.11 | 0.02 | 6.52 |
| | 1 and 3 | 2.62 | 0.01 | 7.97 | 3.41 | 0.06 | 10.76 |
| | 1 and 4 | 1.44 | 0.01 | 4.06 | 5.69 | 0.12 | 17.36 |
| | 2 and 3 | 2.08 | 0.00 | 6.79 | 2.56 | 0.07 | 6.98 |
| | 2 and 4 | 1.31 | 0.00 | 3.95 | 4.20 | 0.33 | 11.21 |
| | 3 and 4 | 1.54 | 0.00 | 4.77 | 2.08 | 0.23 | 4.89 |
| Detection ($\delta$) | 1 and 2 | 6.68 | 0.18 | 20.69 | 0.87 | 0.01 | 2.76 |
| | 1 and 3 | 9.26 | 0.55 | 21.59 | 0.92 | 0.01 | 2.88 |
| | 1 and 4 | 4.57 | 0.14 | 14.13 | 0.48 | 0.01 | 1.47 |
| | 2 and 3 | 2.72 | 0.05 | 8.40 | 1.65 | 0.03 | 4.94 |
| | 2 and 4 | 1.30 | 0.01 | 4.38 | 0.84 | 0.01 | 2.34 |
| | 3 and 4 | 0.65 | 0.03 | 2.05 | 0.71 | 0.05 | 1.85 |

*Table 10. Comparison of mean apparent survival and detection as odds ratios between different intervals between primary periods in Pescara, Italy and Lviv, Ukraine.*

| Average probability | Primary period | Pescara | | | Lviv | | |
|---|---|---|---|---|---|---|---|
| | | Mean | 2.5% CI | 97.5% CI | Mean | 2.5% CI | 97.5% CI |
| Apparent survival ($\varphi$) | 2 to 3 | 4.06 | 0.01 | 11.64 | 2.56 | 0.14 | 6.82 |
| | 2 to 4 | 3.75 | 0.01 | 11.50 | 0.80 | 0.01 | 2.11 |
| | 2 to 5 | 3.12 | 0.00 | 8.37 | 3.05 | 0.07 | 8.38 |
| | 3 to 4 | 1.88 | 0.00 | 5.51 | 0.42 | 0.00 | 1.19 |
| | 3 to 5 | 1.33 | 0.00 | 4.16 | 1.54 | 0.09 | 4.00 |
| | 4 to 5 | 1.49 | 0.00 | 4.36 | 7.81 | 0.16 | 24.16 |
| Detection ($\delta$) | 1 to 2 | 1.70 | 0.31 | 3.71 | 0.65 | 0.29 | 1.07 |
| | 1 to 3 | 1.29 | 0.46 | 2.37 | 0.59 | 0.19 | 1.10 |
| | 1 to 4 | 1.59 | 0.47 | 3.09 | 0.80 | 0.31 | 1.39 |
| | 1 to 5 | 1.10 | 0.20 | 2.40 | 0.87 | 0.31 | 1.56 |
| | 2 to 3 | 0.93 | 0.21 | 1.89 | 0.96 | 0.28 | 1.79 |
| | 2 to 4 | 1.26 | 0.11 | 3.13 | 1.31 | 0.53 | 2.28 |
| | 2 to 5 | 0.71 | 0.23 | 1.34 | 1.38 | 0.66 | 2.27 |
| | 3 to 4 | 1.33 | 0.41 | 2.50 | 1.45 | 0.80 | 2.26 |
| | 3 to 5 | 0.89 | 0.20 | 1.76 | 1.66 | 0.50 | 3.19 |
| | 4 to 5 | 0.79 | 0.09 | 1.78 | 1.14 | 0.45 | 1.96 |
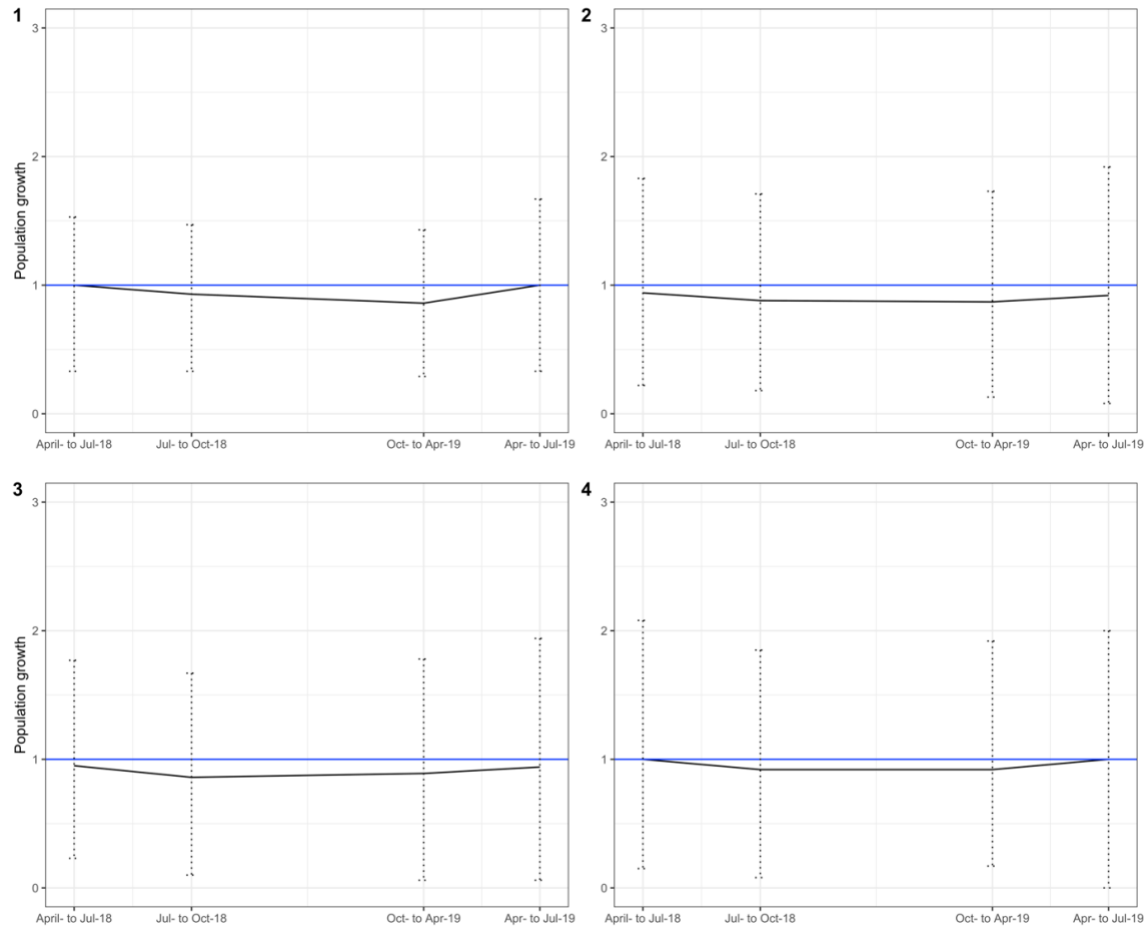
Figure 7. Population growth rates between primary sampling periods in study sites 1 to 4 for study regions Pescara, Italy. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). Blue lines indicate stable population (i.e. no growth or decline). *Note uneven spacing as no surveys conducted in January 2019.
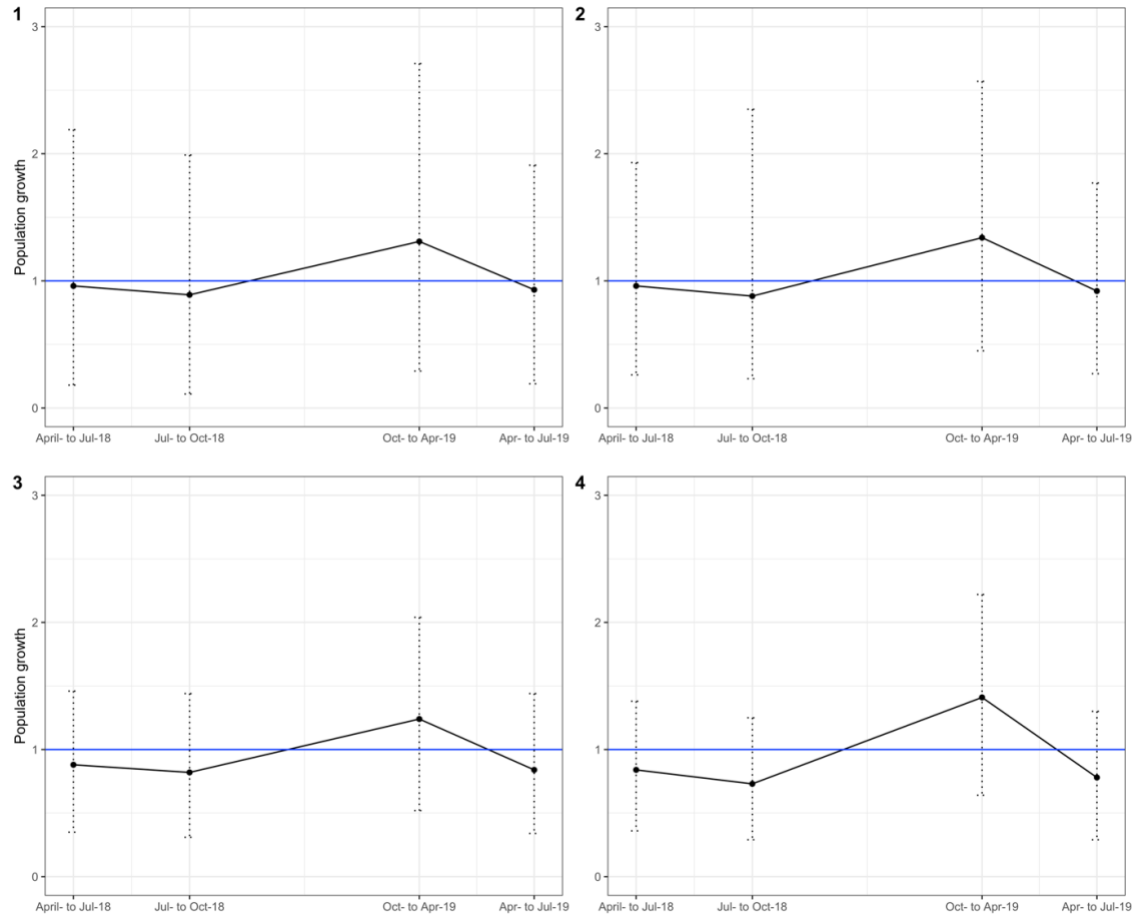
Figure 8. Population growth rates between primary sampling periods in study sites 1 to 4 for study regions Lviv, Ukraine. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). Blue lines indicate stable population (i.e. no growth or decline).* Note uneven spacing as no surveys conducted in January 2019.

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